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SUNFLOWER SOLAR TEST SUPPLEMENT

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TRW Thompson Ramo Wooldridge Inc.

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1. Introduction

This Engineering Report presents a proposal to expand the scope of the Sunflower development program to include solar component and system testing.

The Sunflower proposal, Contract NAS 5-462, provides for a development program which is designed to accomplish the Sunflower Program objectives. It is recognized, however, that there are several supplemental program efforts which could be employed to increase the confidence of meeting the performance and reliability objectives on schedule. Such supplemental efforts are characteristic of any system development program. They include; parallel development programs in critical component areas, increased developmental and reliability testing, greater provision for concurrent component and system development effort, etc.

This proposal urges the expansion of the Sunflower development program to include solar component and system testing. Both the possibility and advisability of this proposal have resulted from the redirection of WADD's SPUD program at Thompson Ramo Wooldridge Inc. This redirection has eliminated plans to utilize the solar test rig to test the SPUD System. WADD has, therefore, made the SPUD rig and equipment available to Thompson Ramo Wooldridge Inc. and The National Aeronautics and Space Administration to support the Sunflower Program.

The proposed program will allow direct experimental determination of full scale collector energy efficiency, and will provide invaluable developmental and operational experience through system testing on solar energy.

A schedule has been developed to accomplish the integration of the Sunflower solar test program to provide test results which can be factored into the Sunflower design.

2. Summary

The following sections present detailed factors related to accomplishing the solar testing of the Sunflower collector and the Sunflower Power Conversion System. The major program provisions are described below.

A. Long Focal Length Collector Tests

The SPUD rig will be modified to accept a forty foot diameter backup collector having a seventeen foot focal length. The forty foot collector is chosen for two reasons. The resultant total intercepted power is in the range of that expected in operation while in orbit; and this size corresponds closely to that required in a possible Mars mission of Sunflower.

The "backup" solar collector will be fabricated similar to the present SPUD collector to be capable of maintaining shape in spite of wind loadings and g forces. It will also provide protection and support for subsequent Sunflower prototype collector tests. The backup forty foot diameter collector will be vacuum metallized and tested optically.

B. System Tests

After completion of the optical test of the forty foot collector, the Sunflower PCS S/N 1 will be installed for collector-system tests. The PCS will have been subjected to development testing in Cleveland and will be made available by the completion of S/N 2 for development testing.

C. Prototype Sunflower Collector Tests

A prototype Sunflower collector will be fabricated and made available for optical tests. This collector will be placed inside the backup collector for environmental protection. Tests of this prototype collector will provide checkout of the collector optics by direct energy measurements.

The following sections include a technical discussion of the feasibility and attraction of the proposed contract supplement, a proposed supplemental statement of work and the proposed Sunflower supplemental development program schedule.

3. Technical Discussion

A. The solar altitude may be equated to declination, latitude and time of day as follows:

$\sin H = \sin D \sin L + \cos D \cos L \cos (360 - \theta)$

Where H = solar altitude - degrees

D = solar declination - degrees

($D = +23\ 1/2^\circ$ on June 21

0° at equinox

$-23\ 1/2^\circ$ on Dec. 21)

L = latitude - degrees (North +)

θ = angular equivalent of time before or after local solar noon - degrees

(1 hour = 15°)

Figure 1 is a plot of these parameters for Los Angeles, California (latitude = $+34^\circ$)

Figure 2 is a plot of solar constant at the surface of the earth as a function of solar altitude on a clear day.

The required solar constant for test of the Sunflower System may be estimated as follows:

Cavity input power requirements

(no excess power for LiH melting)

$P_{req'd} = P_{Hg-sub} + P_{rerad} + P_{convection} + P_{insulation}$

$P_{Hg} = 32.98$ Kw - design point

$$P_{rad} = A \epsilon \sigma T^4$$
$$= 1.13\ ft^2 \times 1 \times .507 \times 10^{-12} \frac{Kw}{ft^2\ {}^\circ R^4} \times 1710^\circ R^4$$
$$= 4.94\ Kw$$

$P_{convection} =$
$= 5.15$ Kw
$P_{insulation} = 1$ Kw

$$\therefore P_{req'd} = 32.98 + 4.94 + 5.15 + 1.0 = 44.07 \text{ Kw}$$

$$P_{intercepted} = \frac{P_{req'd}}{\eta_{coll}} = \frac{44.07}{.738} = 59.8 \text{ Kw}$$

Solar constant required,
(a) 40 foot diameter collector

$$S_{Req} = \frac{59.8 \text{ Kw}}{\frac{\pi}{4}(40^2 - 9.5^2)} = .052 \text{ Kw/ft}^2$$

(b) 32.2 foot diameter collector

$$S_{Req} = \frac{60}{\frac{\pi}{4}(32.2^2 - 9.5^2)} = .081 \text{ Kw/ft}^2$$

These minimum solar constant requirements may be correlated with Figures 2 & 1 to yield Figure 3 which shows useful test hours per day versus season for the 40 and 32.2 foot collectors. Reference to this plot shows that at least five and one half hours of useful test time is obtainable the year around with the forty foot collector, and that two to five and one half hours per day are usable with the 32.2 foot collector during the period from April to October.

B. Proposed Increase of Scope

One of the recognized areas of concern in the development of the Sunflower System is the high cost of discovering design deficiencies in orbit. This concern is amplified by the difficulties involved in simulating operational conditions during development tests. The two most difficult conditions to simulate are "zero g" acceleration and collimated solar energy. Operation of the system in a zero gravity environment requires freefall, ballistic or orbital testing. Such tests are expensive and outside the scope of this proposal. However, utilization of the SPUD rig as proposed can provide data on system operation of the integrated collector system as influenced by gravity "acceleration" of one g in any direction between vertical and 70° from vertical. This will provide important indications of the sensitivity of the system characteristics to gravity acceleration.

According to the Southern California Chamber of Commerce and, incidentally, the United States Weather Bureau, the combination of a forty foot collector and Southern California sunshine will provide sufficient solar energy to simulate a 32.2 foot collector in space. A smaller prototype collector can also operate the system during the summer. Thus, the SPUD rig provides the capability to operate the entire system, including the solar collector, and to maintain performance through transients of energy supply, tracking error, and startup at various gravitational directions.

A strong attraction of the proposed supplement is the opportunity for closer simulation of the operational environment.

The field of solar concentrating systems has lacked to date information on solar collectors operating in the 1500-2000°F range. Thompson Ramo Wooldridge Inc. presently is advancing the state of the art in deployable rigid collectors with the Sunflower Program. However, the Sunflower Program does not presently program actual solar testing of a collector. The contracted program is limited to collimated light and flux distribution testing.

It is expected that solar testing of the collector and PCS will identify problems and suggest operational improvements in the check-out and utilization of the Sunflower System by increasing the developmental coverage in the following areas:

1. Collector

   a) A correlation of contour analyses with measured energy efficiency performance;
   b) Application experience and performance determination for reflecting materials;
   c) A determination of practical limits on collector segment alignment.

2. Orientation Control

   Direct determination of the influence of misorientation on system performance.

3. Receiver-Boiler

   Determination of performance of cavity type receiver, including radiation losses, and performance of the heat storage unit during simulation of sun-shade operation.

4. Rankine Cycle Components

   a) Demonstration of system operational integrity with the solar collector and power conversion system combined.
   b) Determination of the influence of the direction of the gravitational force on system performance.

When the cost of one orbital disappointment is compared with the cost of the proposed incremental improvement in developmental simulation, the value of the proposed supplement is apparent.

C. Description of Existing SPUD Rig

The design concept utilized in the SPUD collector mount and solar tracking system was to provide a simple rugged positioning base for the collector and power conversion system. Several mounting methods were considered for the SPUD design, including equatorial and altitude-azimuth types.

The altitude-azimuth tracking system was chosen for SPUD in preference to the equatorial mount for several reasons:

1. Construction is comparatively simple.
2. The collector and power conversion system may be located closer to the ground affording ease of access and sheltering.
3. The tracking system need only be leveled to the earth regardless of latitude, whereas an equatorial mount requires the polar axis to be adjustable.

The SPUD rig as modified for Sunflower testing is shown in Figure 4.

The collector mount is constructed of conventional structural steel sections. The mount consists of a primary "X" type base frame. A military tank turret race ring and ring gear is attached to the base. A platform is attached to the race ring and can, therefore, rotate about the vertical axis to trace the sun's azimuth. Hinged to this platform is the collector mounting frame. This adjusts for the sun's altitude relative to the horizon. The collector mounting frame supports a fabricated ring which supports the collector as well as the power conversion system.

The solar power conversion system orientation drive utilizes electric motors and mechanical speed reduction equipment. Stock motors and speed reducers were selected to provide the required functions. The azimuth drive consists of a gear motor pinion drive to the tank race ring. The altitude drive consists of a small motor, speed reducer, and screwjacks which are driven by a chain drive from the reducer. Manual operation of each tracking function is accomplished by jog switches. A simple optical alignment device is provided to mount on the collector frame in such a manner that an observer may control the alignment.

Present Status

The SPUD rig currently is assembled through mounting of the collector center dish. The elevation and azimuth drives are assembled. The current physical status is shown in the photographs of Figure 5.

D. Modifications to Existing SPUD Rig

The Sunflower Solar Test Rig is shown in Figure 4. The SPUD rig was originally designed to track the sun within $\pm 5^{\circ}$ by the use of A.C. drive motors and jog switches. However, the Sunflower cavity receiver concept operates at a higher concentration ratio than was intended for SPUD, thus is more sensitive to tracking errors.

The proposed modification to the existing rig to improve solar tracking are as follows:

1. Add reinforcing member to the main rotating platform.
2. Repair tank race ring bearing to eliminate excessive play.
3. Convert A.C. - jog drive motors to D.C. motors and controls to operate from an error signal generated by a solar sensing device for automatic tracking.
4. Replace the existing elevation arm with a selectable length arm which will allow the necessary adjustments to be made for summer and winter testing without rig disassembly and modification.

The following design changes will be made to accommodate the Sunflower System:

1. An adapter section will be added to allow for attachment of the Sunflower collector and PCS and to provide for supporting truss ribs.
2. Honeycomb ribs will be added to provide a backup structure which will aid in collector assembly and restrict deflection during wind loading.
3. Provisions will be incorporated for mounting both the forty foot diameter backup collector and the Sunflower prototype collector.
4. A base structure is provided for the mounting of the power conversion system to the adapter section.
5. Move the physical location of the rig to clear the adjacent building with the forty foot diameter paraboloid installed.

To obtain more testing time during the winter months in California, it is desirable to increase the length of the elevation arm to accommodate testing with the forty foot collector at a solar altitude of 20^{o}.

Provision will also have to be made to give the system a ground clearance 2 1/2 feet in excess of that shown on Figure 4 because of the 20^{o} altitude alignment position of the system.

4. Proposed Program

The proposed program is presented graphically in Figure 6. Reference to this figure indicates the tasks and the chronological order in which they are to be performed.

The initial effort shall be directed toward accomplishing the required redesign and modification of controls, instrumentation, and rig to operate the Sunflower System. The SPUD rig shall be modified to provide for automatic tracking of the sun. This task will involve a detailed study to determine the effects of the Sunflower Power Conversion System installation upon the rig due to shifts in location of the boiler, condenser, collector and system hardware. Also, to accurately track the sun within $\pm$ $1/4^{o}$, the rig will be modified to reduce deflections and backlash. This modification shall also provide the capability of accepting the Sunflower Power Conversion System for combined collector and PCS testing.

A forty foot backup paraboloid will be fabricated of the fiberglass and honeycomb construction used in the SPUD collector. This structure will be formed on the Sunflower prototype collector mold and will have adequate strength to withstand the testing environment of wind, and "G" forces. The inner surface of this structure will be vacuum metallized and have the capability of being used as a forty foot diameter, seventeen foot focal length collector. The forty foot collector is selected to approximate the heat flux input at the boiler cavity expected in orbital sun operation. The heavy duty forty foot collector will be installed in the solar test rig and checkout and optical tests shall be conducted. Testing of the collector shall include optical testing to determine optical efficiency and target flux distribution as a function of concentration ratio and misorientation.

A complete Sunflower Power Conversion System will be installed in the rig. The instrumentation shall be specifically redesigned to account for the effects of changing liquid head on the recorded date.

The primary objectives of the Sunflower System tests on the SPUD rig will be directed at demonstrating system operational integrity with the combined solar collector and power conversion system. Tests will be conducted to determine the influence of misorientation on system performance, and the effect of gravitational force on system operation. Test conditions will be imposed to simulate continuous sun and cyclic sun-shade conditions. System startup, shut down, and re-ready for start shall be demonstrated.

After the completion of this system testing, a Sunflower prototype solar collector will be installed within the backup structure, and a complete collector checkout similar to that described above for the forty foot collector will be performed.

The ground checkout system otherwise required in the Sunflower contract shall be employed to operate the system during the development tests. This checkout system shall be constructed with as many of the SPUD auxiliary and instrumentation components as can feasibly be used in synthesizing a system to operate Sunflower. Of particular interest in the utilization of SPUD equipment are the dynamic recorders, temperature loggers, gages, tranducers, and similar type hardware. A list of the usable equipment from the SPUD Program and assumed available to the proposed Sunflower supplement is included in the cost attachment.

It is intended to use PCS S/N 1 as the system to be installed in the solar test rig. This hardware will be employed for integrated testing with both the forty foot heavy duty collector and subsequent tests with the prototype Sunflower collector. It has been assumed that the equivalent of one set of major components will be required as spares for PCS S/N 1 to accomplish the total solar test program.

5. Preliminary Statement of Work

This section contains the proposed supplemental statement of work. It has been prepared in the form of a contract supplement to NAS 5-462 and is based on the acceptance of the modifications proposed by letter of August 27, covering the lithium hydride properties supplement.

Amend Article 1 (a) of the Schedule by adding the following at the end of the subparagraph entitled Phase I thereof:

7. Design and modification shall be performed of the SPUD rig for automatic solar tracking.

In the same article add to Phase II the following:

8. Design modifications shall be made to the SPUD rig to accept a backup structure and Sunflower Solar Collector.
9. The backup structure shall be installed and optical tests of the Sunflower collector performed on the modified rig.
10. The ground checkout system to be utilized with tests on the power conversion system solar test shall be designed and fabricated. Integrated system tests with the Sunflower collector, power conversion system, and ground checkout equipment shall be conducted.

Amend Article 1 (b) of the Schedule by deleting the fourth paragraph thereof and adding the following paragraph at the end:

In addition, upon request of NASA, a total of eight topical reports, teletype reports and special analyses shall be provided. One of the topical reports shall be a reliability analysis submitted with delivery of the two flight prototypes. A second topical report shall cover the investigation of thermal properties of lithium hydride described in Exhibit B, paragraph 14, thereof. A third topical report shall be submitted on the results of the optical and integrated power conversion system testing on the SPUD rig. This report shall be submitted within thirty days after completion of the relevant development test effort.

Article (2)

In the first line change 4,117,680 to read 5,040,432.
In the second line change 254,738 to read 319,330.
In the third line change 4,372,418 to read 5,359,762.

Exhibit B, amend paragraph 10 as follows:

10. Ground Checkout System

This task covers the design and procurement of the system required to provide prelaunch checkout of the Sunflower I System. This activity is closely related to the design and fabrication of the acceptance test facility and the facility which will be employed to operate the Sunflower solar tests. The design of this system is essentially a design adaptation of these facilities for field use.

Phase I

A ground checkout system shall be designed and constructed with as many of the SPUD auxiliary and instrumentation components as can feasibly be used in synthesizing this system.

Phase II

Construct and operate the 40 foot collector and power conversion system tests with ground checkout system.

Incorporate into the design of the Sunflower ground checkout system the improvements and modifications gained from the Sunflower solar test system.

Exhibit B, add the following as paragraph 15:

15. Sunflower Solar Test Program

This shall consist of change modifying and completing the assembly of the SPUD rig, both to be provided by the government as a result of the partial completion of the original SPUD Contract (AF 3 etc.) with WADD of the United States Air Force. The rig will be modified to accept a backup structure collector and a Sunflower collector for optical testing and ultimately for solar testing of the Sunflower Power Conversion System.

This program shall consist of approximately eighteen months activity. The results of the optical and system testing are to be factored into the design modifications of Sunflower in order to arrive at the most reliable overall system for delivery to NASA.

The contractor shall complete the solar test program during Phases I, II, and III of the Sunflower Program. Tasks to be completed in each phase are outlined below:

Phase I

1. Design study and modification will be made to SPUD rig to prepare for the automatic tracking and system testing which is to be accomplished during Phase I and II.

Phase II

1. The ground checkout system shall be designed and fabricated to operate the system and monitor system performance.
2. A backup paraboloid structure and a prototype Sunflower collector shall be fabricated for integrated testing on the modified Sunflower solar test rig.
3. Spare major components of the power conversion system shall be fabricated as spares and employed with PCS S/N 1 for system testing in the modified Sunflower solar test rig.
4. Four months of system solar development testing shall be completed.

Phase III

1. The Sunflower prototype collector shall be installed.
2. The Sunflower collector shall be optically tested.
3. A final report on collector and system solar testing shall be submitted.

SOLAR ALTITUDE VERSUS TIME
(FOR 34° N. LATITUDE)

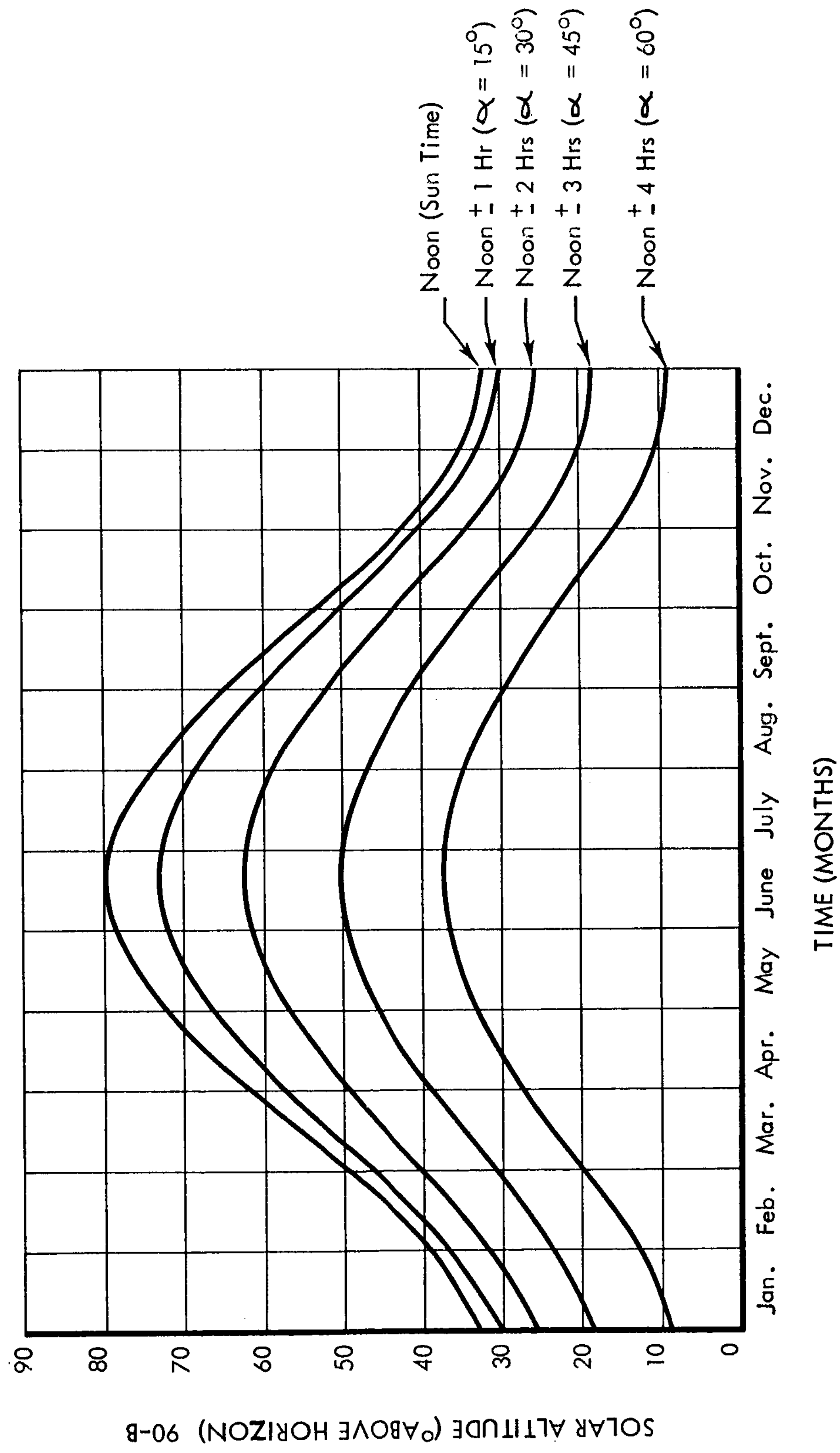


FIGURE 1

SOLAR ALTITUDE VS. NORMAL RADIATION

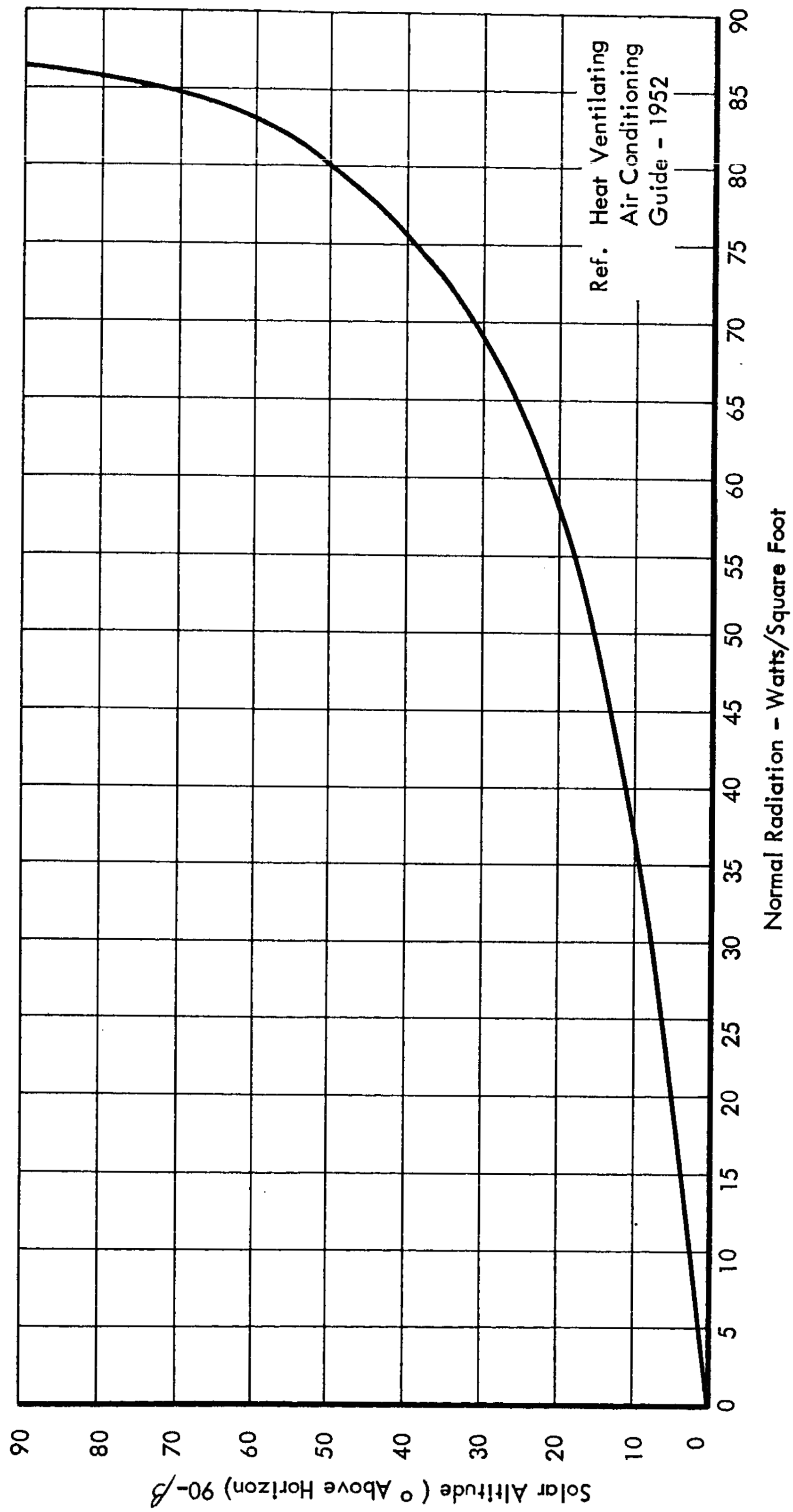


FIGURE 2

TEST TIME Vs. MONTH AT 34° LATITUDE - CLEAR SKY

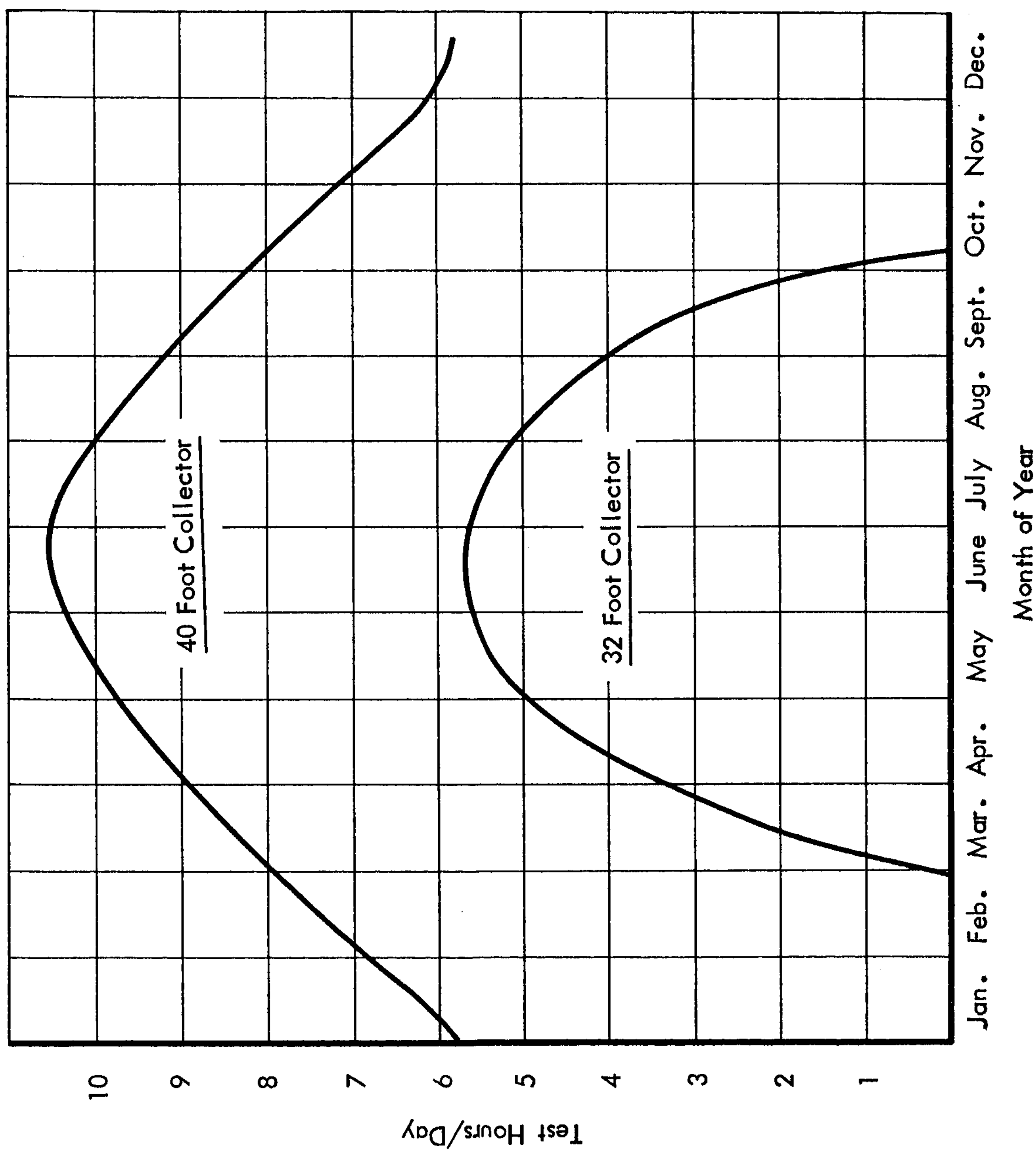
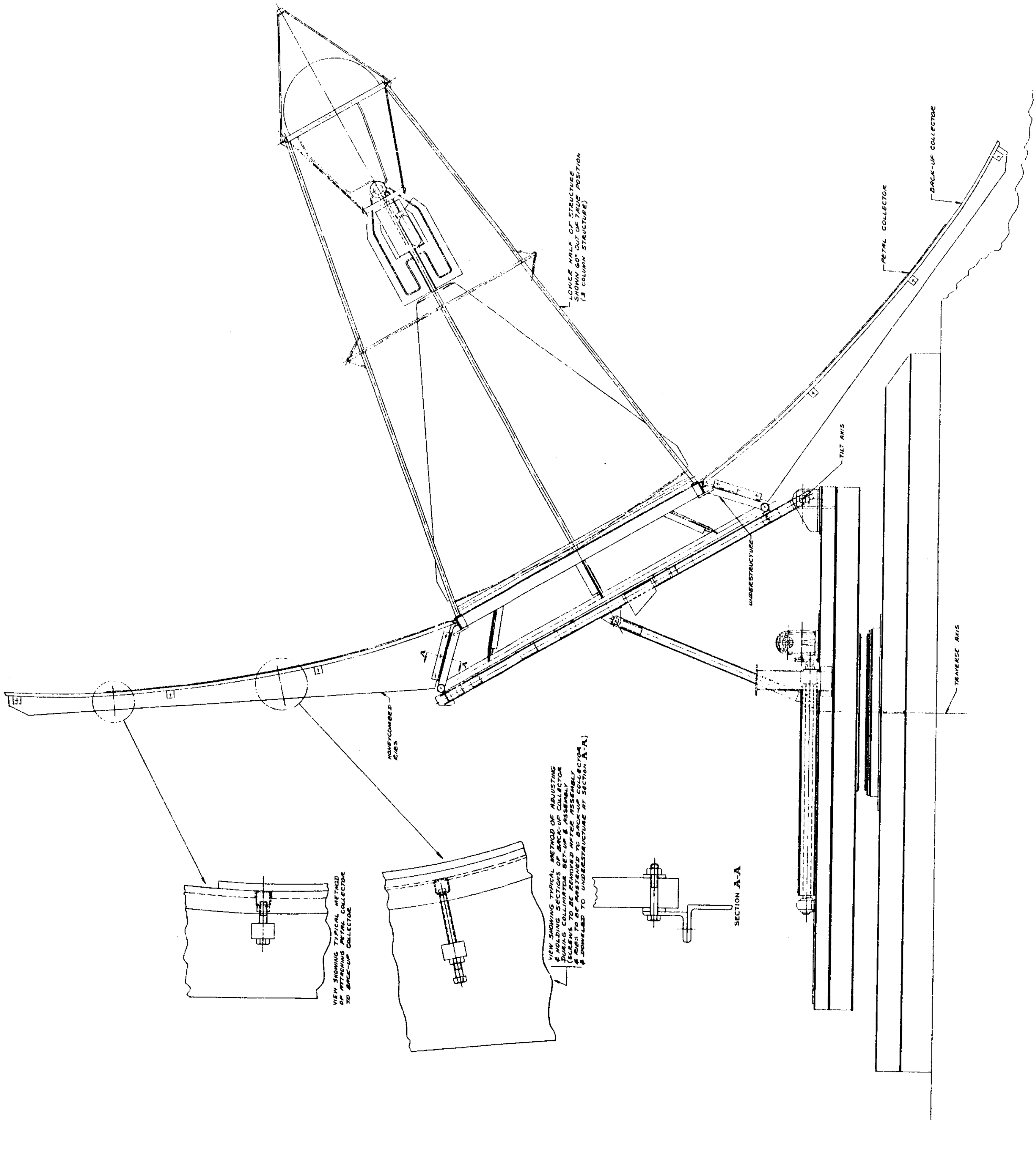


FIGURE 3


LOWER HALF OF STRUCTURE SHOWN 60° OUT OF TRUE POSITION (3 COLUMN STRUCTURE)
BACK-UP COLLECTOR
PETAL COLLECTOR
TILT AXIS
UNDERSTRUCTURE
TRAVERSE AXIS
HONEYCOMBED RIBS
VIEW SHOWING TYPICAL METHOD OF ADJUSTING & HOLDING SECTIONS OF BACK-UP COLLECTOR DURING COLLIMATOR SET-UP & ASSEMBLY (SLEEVES TO BE REMOVED AFTER ASSEMBLY & RIBS TO BE FASTENED TO BACK-UP COLLECTOR & DOWELED TO UNDERSTRUCTURE AT SECTION A-A)
SECTION A-A
VIEW SHOWING TYPICAL METHOD OF ATTACHING PETAL COLLECTOR TO BACK-UP COLLECTOR

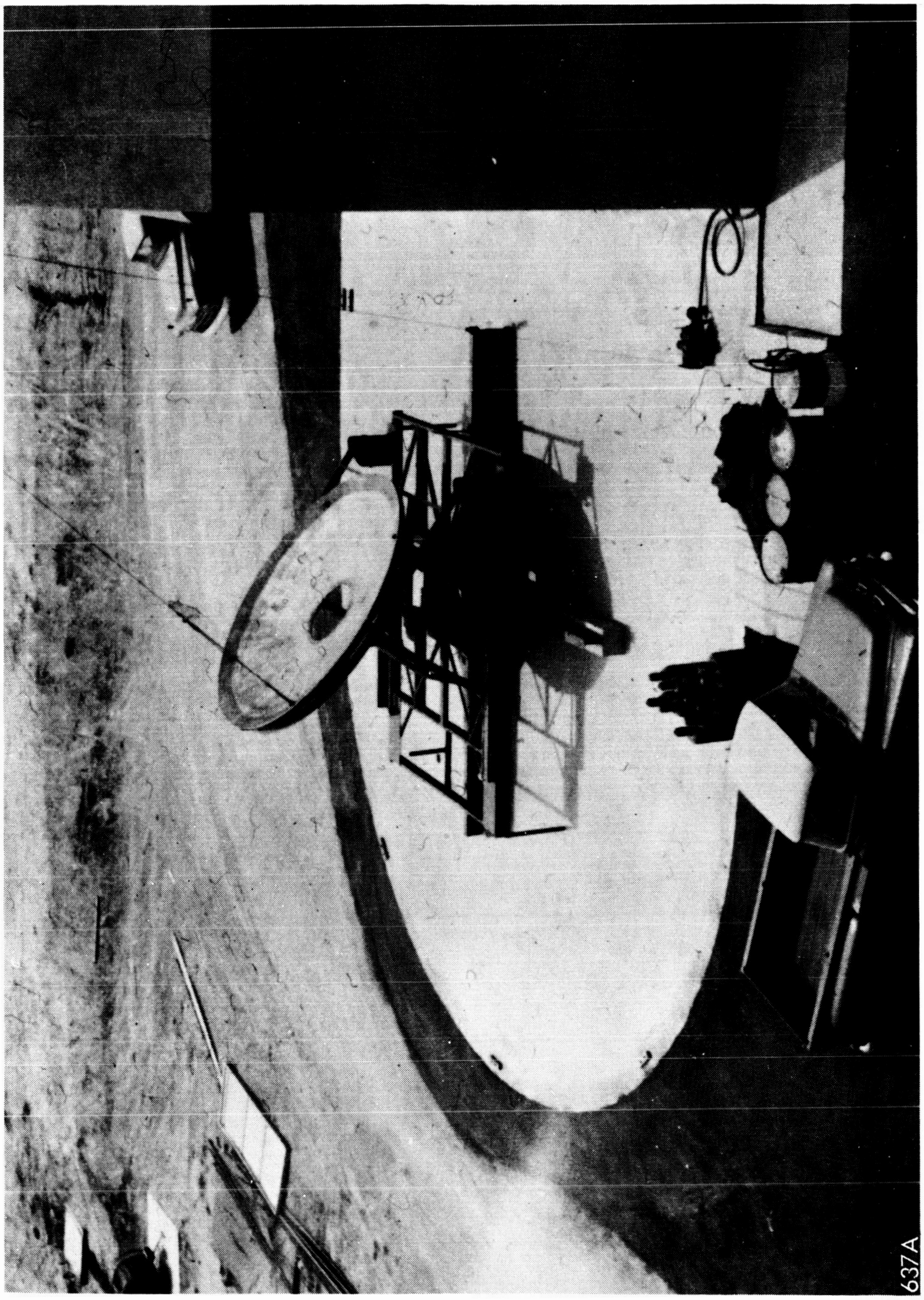


FIGURE 5a

FIGURE 5b

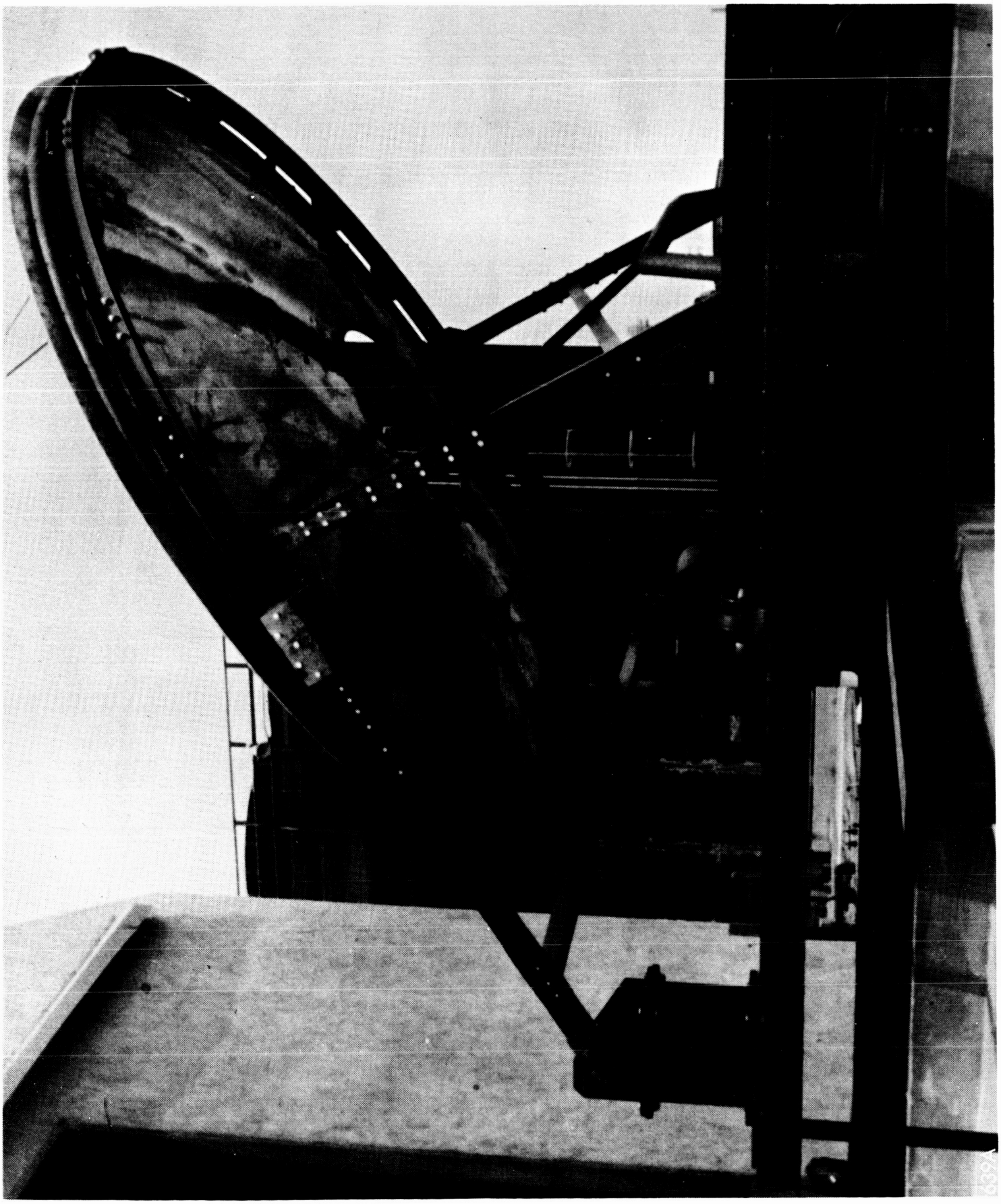


FIGURE 5c

PROGRAM CHART

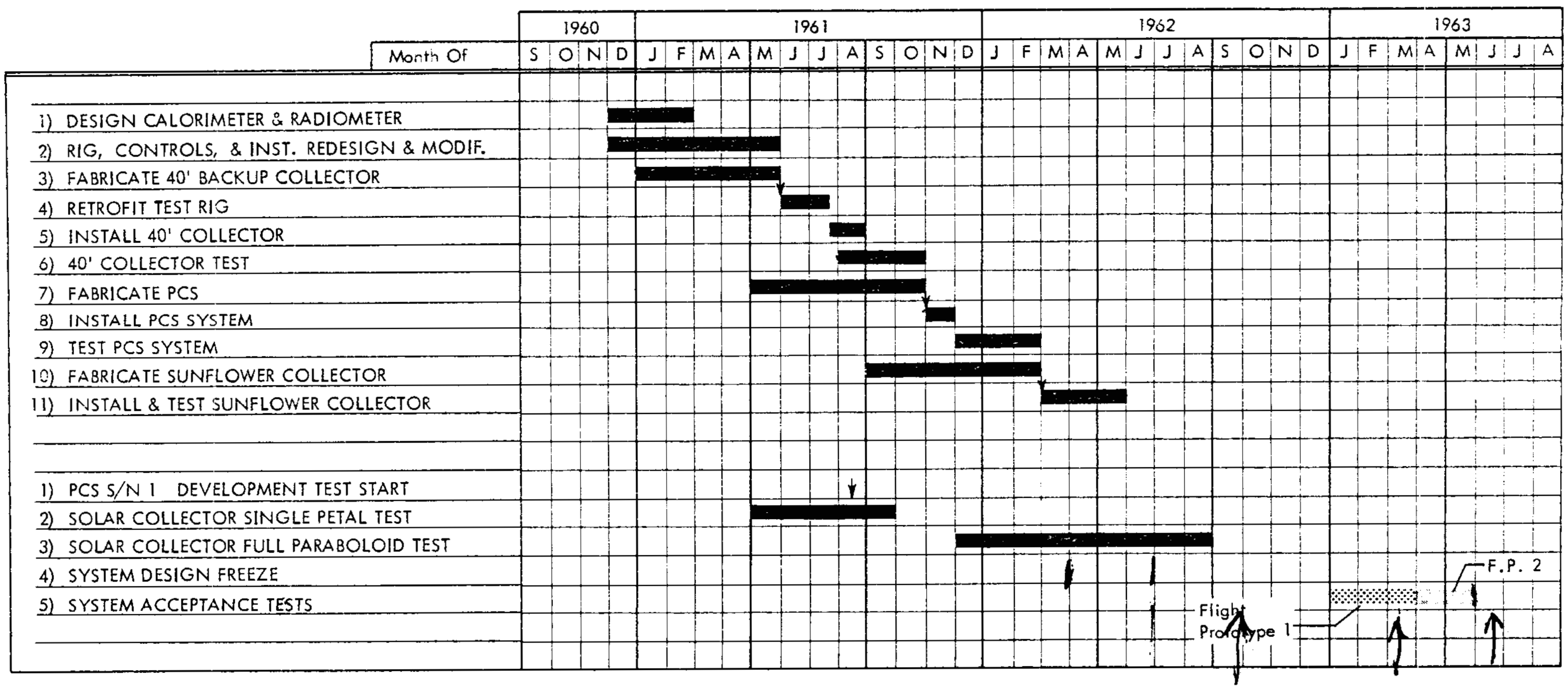


FIGURE 6